Chapter 4: Threads & Concurrency

Chapter 4: Threads

- Overview
- Multicore Programming
- Multithreading Models
- Thread Libraries
- Implicit Threading
- Threading Issues
- Operating System Examples

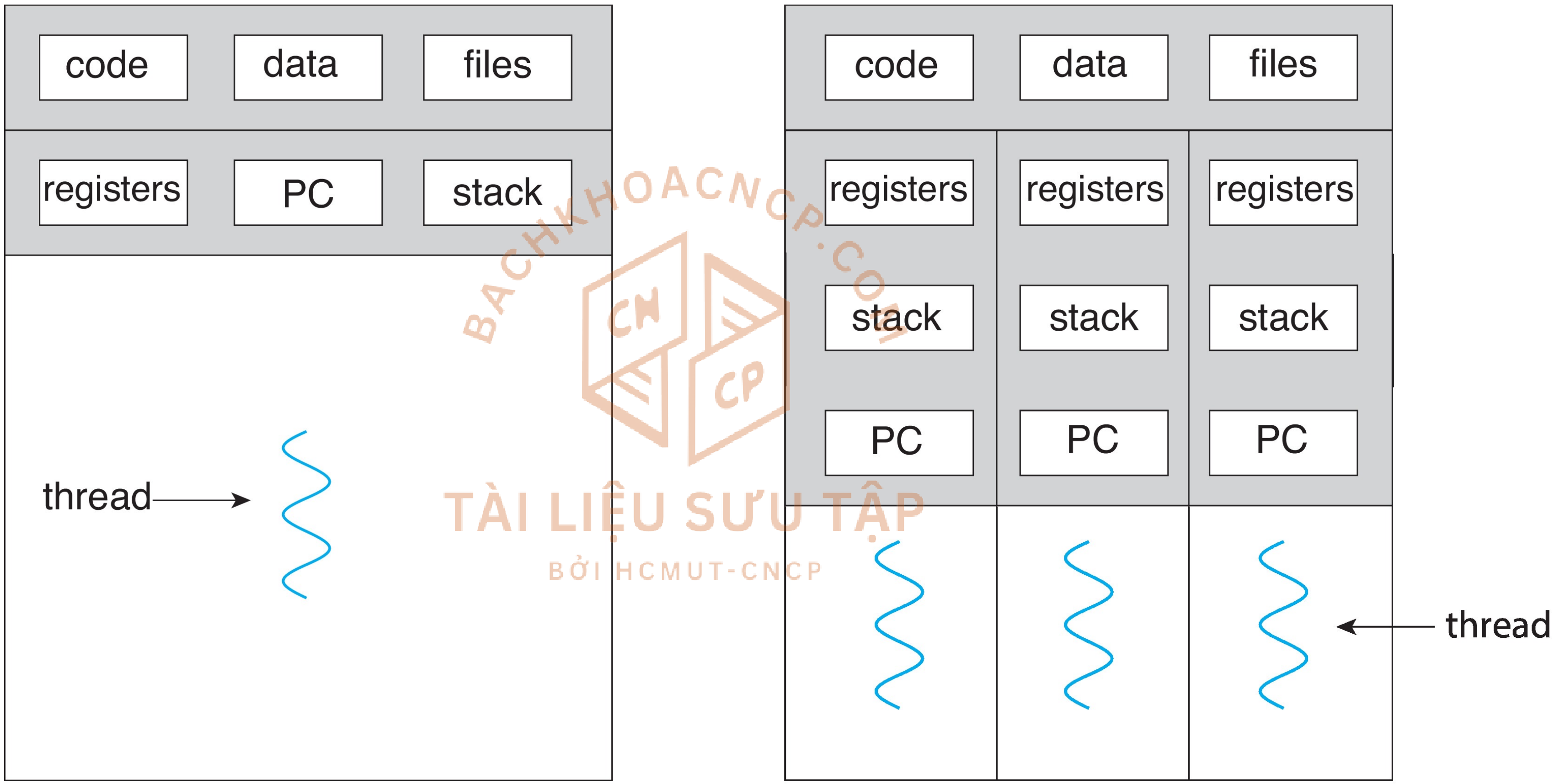
Objectives

- Identify the *basic components of a thread*, and *contrast threads and processes*
- Describe the *benefits* and *challenges* of designing *multithreaded applications*
- Illustrate *different approaches to implicit threading* including thread pools, fork-join, and Grand Central Dispatch
- Describe how the Windows and Linux operating systems represent threads
- Design multithreaded applications using the Pthreads, Java, and Windows threading APIs

Motivation

- Most modern applications are *multithreaded*
- *Threads run within application*
- Multiple tasks with the application can be implemented by separate threads
  - Update display
  - Fetch data
  - Spell checking
  - Answer a network request
- Process creation is heavy-weight while *thread creation is light-weight*
- Can simplify code, increase efficiency
- Kernels are generally multithreaded

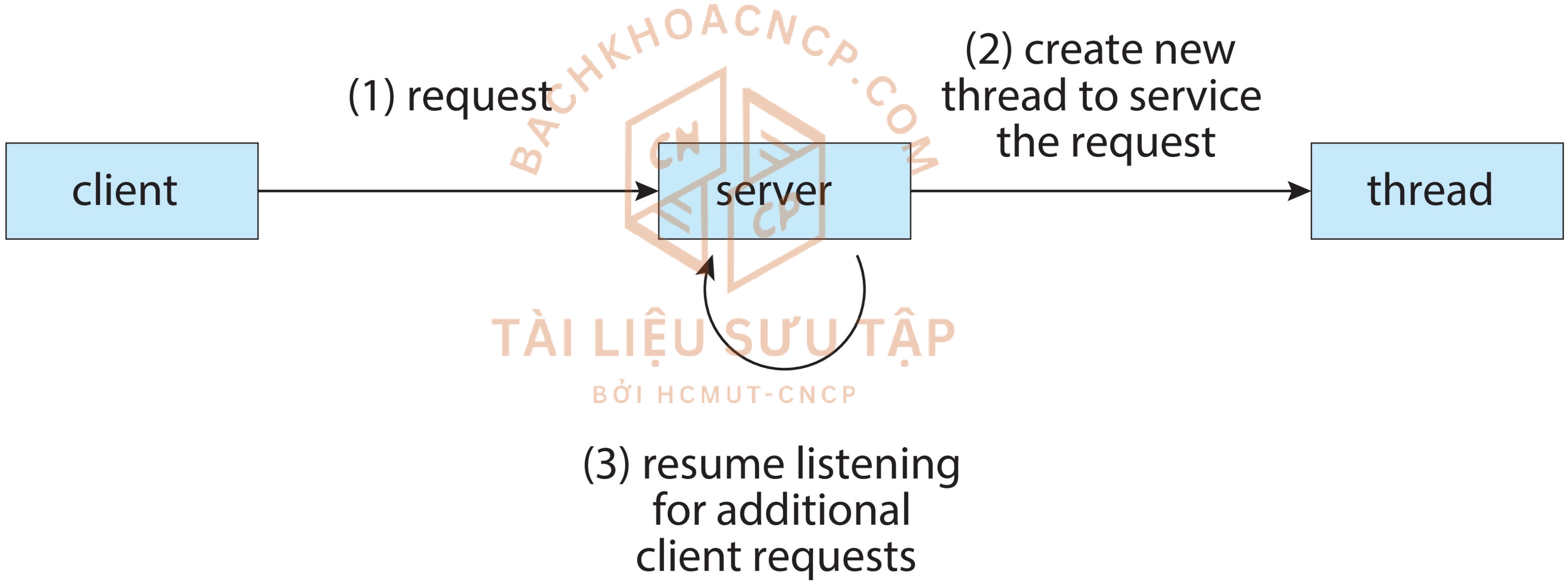
Single and Multithreaded Processes



single-threaded process

multithreaded process

Multithreaded Server Architecture



Benefits

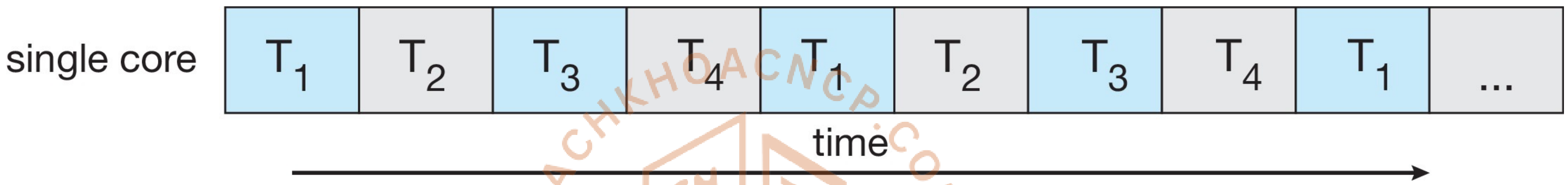
- *Responsiveness* – may allow continued execution if part of process is blocked, especially important for user interfaces
- *Resource Sharing* – threads share resources of process, easier than shared memory or message passing (IPC)
- *Economy* – cheaper than process creation, thread switching lower overhead than context switching
- *Scalability* – process can take advantage of multicore architectures

Multicore Programming

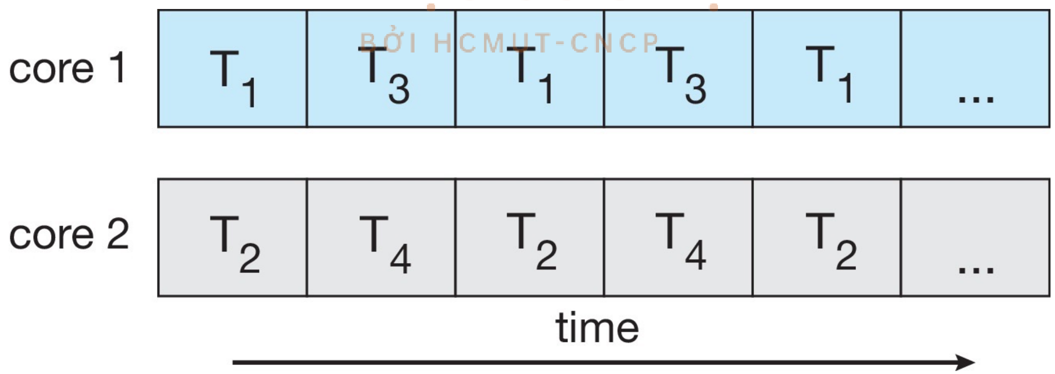
- *Multicore* or *multiprocessor systems* putting pressure on programmers, challenges include:
  - Dividing activities
  - Balance
  - Data splitting
  - Data dependency
  - Testing and debugging
- *Parallelism* implies a system can perform more than one task simultaneously
- *Concurrency* supports more than one task making progress
  - Single processor / core, scheduler providing concurrency

Concurrency vs. Parallelism

- Concurrent execution on single-core system:



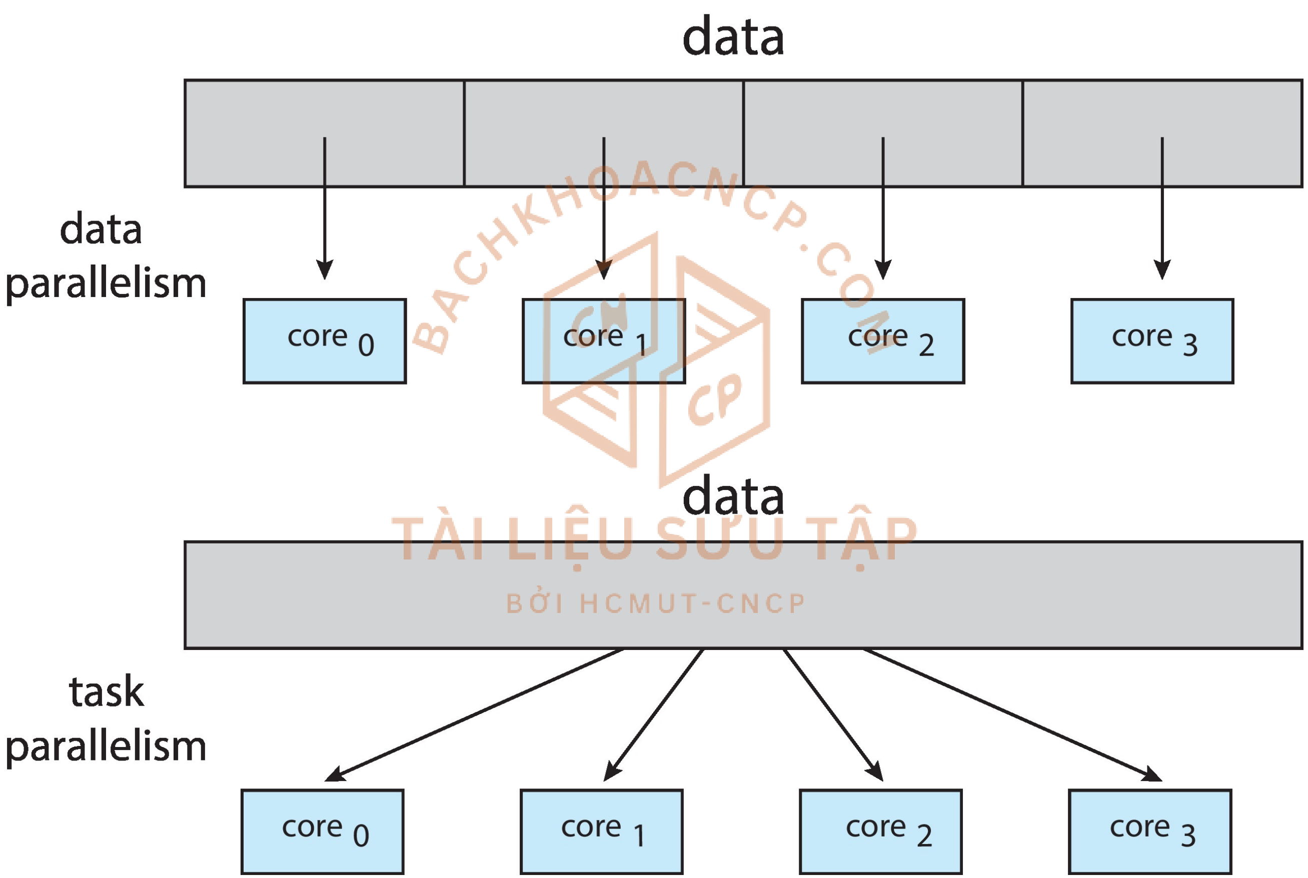
- Parallelism on a multi-core system:



Multicore Programming

- Types of parallelism
  - ***Data parallelism*** – distributes subsets of the same data across multiple cores, same operation on each
  - ***Task parallelism*** – distributing threads across cores, each thread performing unique operation

Data and Task Parallelism



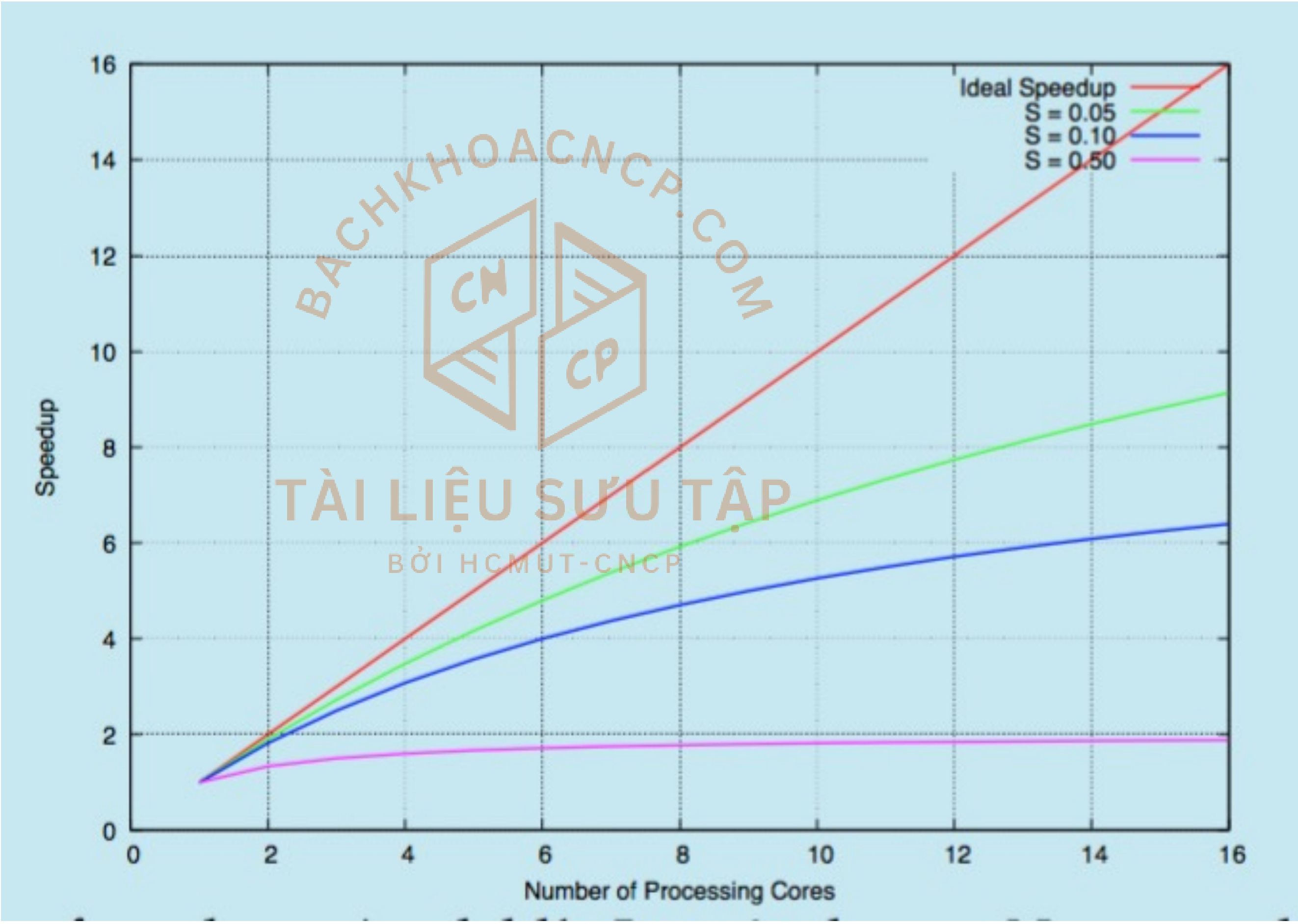
Amdahl's Law

- Identifies *performance gains* from adding additional cores to an application that has both serial and parallel components
  - **S** is serial portion
  - **N** processing cores

  $$speedup \leq \frac{1}{S + \frac{(1-S)}{N}}$$

  - That is, if application is 75% parallel / 25% serial, moving from 1 to 2 cores results in speedup of 1.6 times
  - As **N** approaches infinity, speedup approaches **1/S**
- Serial portion of an application has disproportionate effect on performance gained by adding additional cores
- But does the law take into account *contemporary multicore systems*?

Amdahl's Law

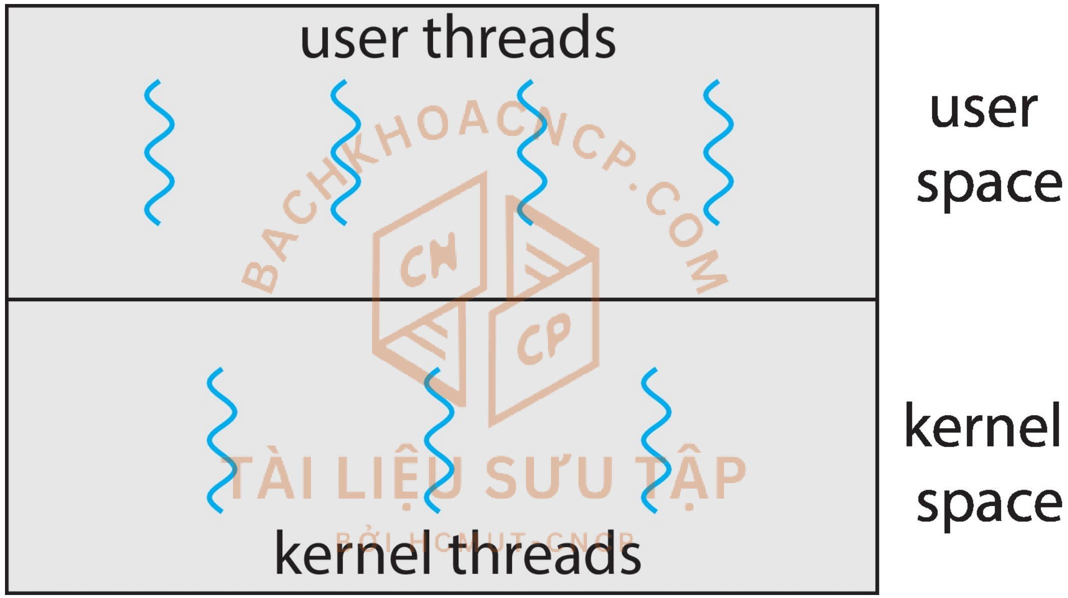


Ideal Speedup
S = 0.05
S = 0.10
S = 0.50
Speedup
Number of Processing Cores
0
2
4
6
8
10
12
14
16

User Threads and Kernel Threads

- *User threads* - management done by user-level threads library
- Three primary thread libraries:
  - POSIX Pthreads
  - Windows threads
  - Java threads
- *Kernel threads* - supported by the Kernel
- Examples – virtually all general purpose operating systems, including:
  - Windows, Linux, Mac OS X
  - iOS, Android

User and Kernel Threads

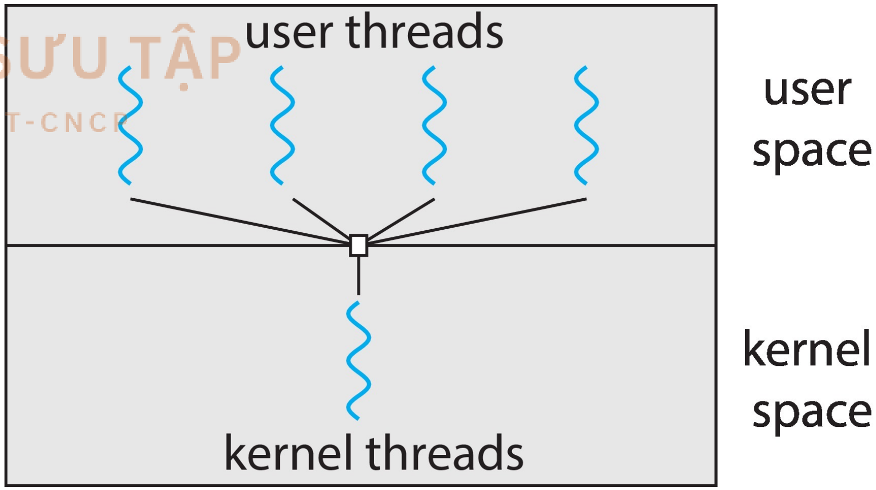


Multithreading Models

- Many-to-One
- One-to-One
- Many-to-Many

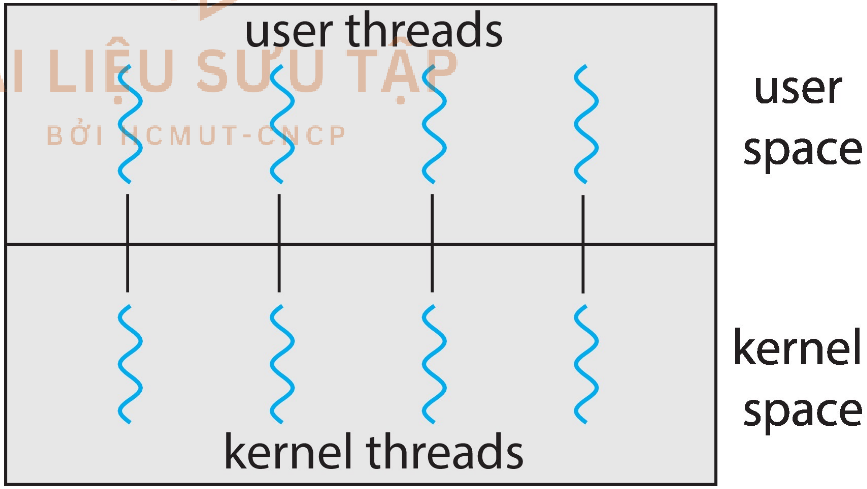
Many-to-One

- *Many user-level threads* mapped to *single kernel thread*
- One thread blocking causes all to block
- Multiple threads may not run in parallel on multicore system because only one may be in kernel at a time
- *Few systems currently use this model*
- Examples:
  - Solaris Green Threads
  - GNU Portable Threads



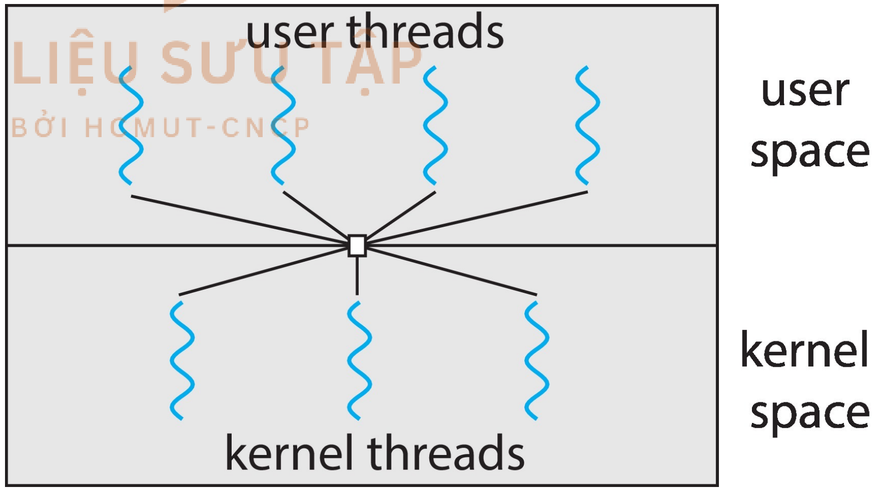
One-to-One

- *Each user-level thread* maps to *one kernel thread*
- Creating a user-level thread creates a kernel thread
- More concurrency than many-to-one
- Number of threads per process sometimes restricted due to overhead
- Examples
  - Windows
  - Linux



Many-to-Many Model

- Allows *many user level threads* to be mapped to *many kernel threads*
- Allows the operating system to create a sufficient number of kernel threads
- Windows with the **`ThreadFiber`** package
- Otherwise *not very common*



Thread Libraries

- ***Thread library*** provides programmer with API for creating and managing threads
- Two primary ways of implementing
  - Library entirely *in user space*
  - Kernel-level library *supported by the OS*

Pthreads

- May be provided either as *user-level* or *kernel-level*
- A **POSIX standard (IEEE 1003.1c) API** for thread creation and synchronization
- Specification, not implementation
- API specifies behavior of the thread library, implementation is up to development of the library
- Common in UNIX operating systems (Linux & Mac OS X)

Pthreads Example

```
#include <pthread.h>
#include <stdio.h>

#include <stdlib.h>

int sum; /* this data is shared by the thread(s) */
void *runner(void *param); /* threads call this function */

int main(int argc, char *argv[])
{
   pthread_t tid; /* the thread identifier */
   pthread_attr_t attr; /* set of thread attributes */

   /* set the default attributes of the thread */
   pthread_attr_init(&attr);
   /* create the thread */
   pthread_create(&tid, &attr, runner, argv[1]);
   /* wait for the thread to exit */
   pthread_join(tid,NULL);

   printf("sum = %d\n",sum);
}
```

Pthreads Example (cont)

```
/* The thread will execute in this function */
void *runner(void *param)
{
   int i, upper = atoi(param);
   sum = 0;

   for (i = 1; i <= upper; i++)
      sum += i;

   pthread_exit(0);
}
```

Pthreads Code for Joining 10 Threads

```
#define NUM_THREADS 10

/* an array of threads to be joined upon */
pthread_t workers[NUM_THREADS];

for (int i = 0; i < NUM_THREADS; i++)
   pthread_join(workers[i], NULL);
```

Implicit Threading

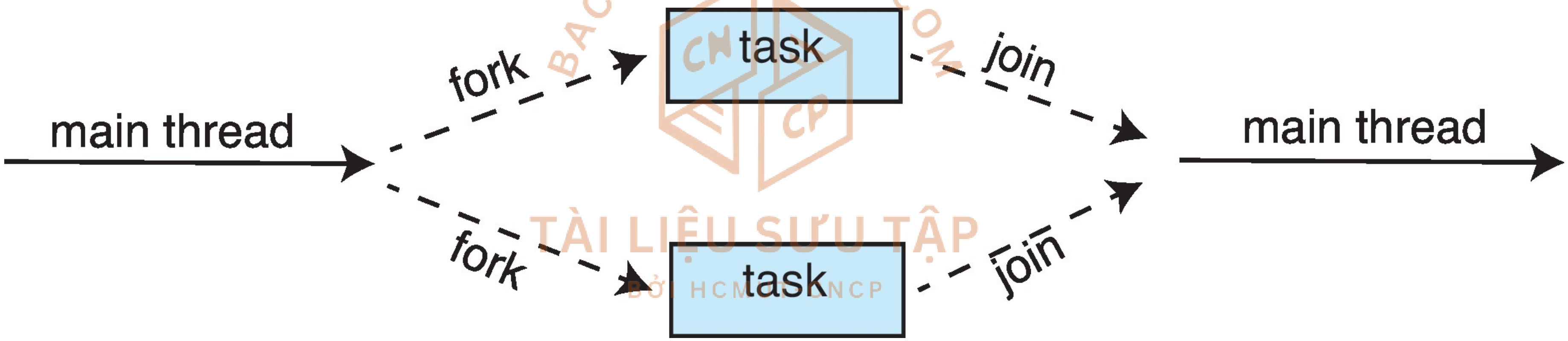
- Growing in popularity as numbers of threads increase, program correctness more difficult with *explicit threads*
- *Creation and management of threads done by compilers and run-time libraries* rather than programmers
- Five methods explored
  - Thread Pools
  - Fork-Join
  - OpenMP
  - Grand Central Dispatch
  - Intel Threading Building Blocks

Thread Pools

- Create a *number of threads in a pool* where they await work
- Advantages:
  - Usually slightly *faster* to service a request with an existing thread than create a new thread
  - Allows the number of threads in the application(s) to be *bound* to the size of the pool
  - Separating task to be performed from mechanics of creating task allows different strategies for running task
    - i.e., Tasks could be scheduled to run periodically

Fork-Join Parallelism

- *Multiple threads (tasks) are forked*, and then *joined*.



Fork-Join Parallelism

- General algorithm for *fork-join strategy*:

```
Task(problem)
   if problem is small enough
      solve the problem directly
   else
      subtask1 = fork(new Task(subset of problem)
      subtask2 = fork(new Task(subset of problem)

      result1 = join(subtask1)
      result2 = join(subtask2)

      return combined results
```

Threading Issues

- Semantics of **`fork()`** and **`exec()`** system calls
- Signal handling
  - Synchronous and asynchronous
- Thread cancellation of target thread
  - Asynchronous or deferred
- Thread-local storage
- Scheduler Activations

Semantics of fork() and exec()

- Does **`fork()`** duplicate only the calling thread or all threads?
  - Some UNIXes have two versions of fork
- **`exec()`** usually works as normal – replace the running process including all threads

Signal Handling

- *Signals* are used in UNIX systems to notify a process that a particular event has occurred.
- A *signal handler* is used to process signals
  - Signal is generated by particular event
  - Signal is delivered to a process
  - Signal is handled by one of two signal handlers
    - default
    - user-defined

- Every signal has a default handler that kernel runs when handling signal
  - User-defined signal handler can override default
  - For single-threaded, signal delivered to process

Signal Handling (Cont.)

- *Where* should a signal be delivered for *multi-threaded*?
  - Deliver the signal to the thread to which the signal applies
  - Deliver the signal to every thread in the process
  - Deliver the signal to certain threads in the process
  - Assign a specific thread to receive all signals for the process

Thread Cancellation

- Terminating a thread before it has finished
- Thread to be canceled is target thread
- Two general approaches:
  - Asynchronous cancellation terminates the target thread immediately
  - Deferred cancellation allows the target thread to periodically check if it should be cancelled
- **Pthread** code to create and cancel a thread:

```
pthread_t tid;

/* create the thread */
pthread_create(&tid, 0, worker, NULL);

. . .

/* cancel the thread */
pthread_cancel(tid);

/* wait for the thread to terminate */
pthread_join(tid,NULL);
```

Thread Cancellation (Cont.)

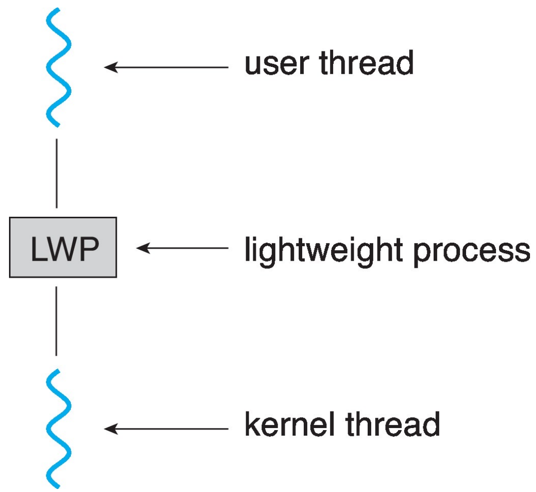
- Invoking thread cancellation requests cancellation, but actual cancellation depends on thread state

Mode	State	Type
Off	Disabled	–
Deferred	Enabled	Deferred
Asynchronous	Enabled	Asynchronous

- If thread has cancellation disabled, cancellation remains pending until thread enables it
- Default type is deferred
  - Cancellation only occurs when thread reaches cancellation point
    - i.e., `pthread_testcancel()`
    - Then cleanup handler is invoked
- On Linux systems, thread cancellation is handled through signals

Scheduler Activations

- Both M:M and Two-level models require communication to maintain the appropriate number of kernel threads allocated to the application
- Typically use an intermediate data structure between user and kernel threads – *lightweight process* (**LWP**)
  - Appears to be a *virtual processor* on which process can schedule user thread to run
  - Each LWP attached to kernel thread
  - How many LWPs to create?
- Scheduler activations provide upcalls - a communication mechanism from the kernel to the upcall handler in the thread library
- This communication allows an application to maintain the correct number kernel threads



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